Criterion of steam generating ducts parametrical similarity.

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Abstract:

The mathematical model worked out for parametrical oscillations of the coolant due to a periodic change in the elasticity of the latter enables us to determine the boundary (critical) value of the modulation of this parameter. When it is reached, parametrical oscillations (of the pressure, the flow rate, and other parameters) are excited in the coolant. This model for revealing in more detail the dynamic processes in the coolant of the passive protection systems for the core was proved to be applicable.

Key words: simulation, oscillation, safety, thermal-hydraulic, dimensionless product.

AMS subject classifications: 76E09, 76E19, 34C60

1 Introduction

The use of different thermal-hydraulic computer codes for pre and post-test calculations is an important part of the work programme for activities in the field of Nuclear Power Plants (NPP) Safety Research as it will enable to define better the test configuration and parameter range extensions and to extrapolate the results of the small scale experiments towards full scale reactor applications [1].
The WCOBRA/TRAC [2], CATHARE2, RELAP5 [3] and APROS [4] codes are the estimate thermal hydraulic codes for the evaluation of large and small break loss of coolant accidents (LOCA). The relatively good agreement experimental data with the calculations have been presented [2, 3]. There also was shown some big mistakes in predicting distribution of flow when two phase are present. Model of parametrical oscillations (P.O.) worked out gives explanation for flow oscillations and indicates that the phenomenon of P.O. appears under certain combination of thermal-hydraulic parameters and structure of heat-removal system.

2 Background

In 1996 a new project for the investigation of passive safety injection systems (PSIS's) of the Advanced Light Water Reactor (ALWR) begun. The new project is a part of INNO cluster of the European Commission Nuclear Fission Safety (NFS-2) Programme.
2.1 The PSIS investigated [4] consists of a passive Core Make-Up Tank (CMT), Pressure Balancing Line(s) (PBL(s)) and an Injection Line (IL). The IL connected the CMT to the downcomer. The PBL's connected the CMT to one cold leg and to the top of the pressurised.
The purpose of the PSIS is to inject water to the reactor in Loss-of-Coolant accidents. The system replace the high pressure safety injection systems of the existing nuclear power plants. These experiments have provided valuable, information about phenomena in the PSIS during Small Break Loss-Of-Coolant Accidents (SBLOCA's). The main phenomena of interest are thermal stratification in the CMT, heat transfer and condensation processes in the tank, and natural circulation flow through the PSIS lines. Computer code analyses of the experiments

have shown that the existing thermal-hydraulic computer codes need further development, the main problems being connected with the simulation of thermal stratification and condensation phenomena in the CMT during Emergency Core Cooling (ECC) injection. Also the situations where the driving head for natural circulation flow is small seems to be difficult for the codes to simulate.

CATHARE and RELAP5 codes have been used to help analyse the GDE-05 experiment from the first passive safety injection experiment series. The purpose of the CATHARE and RELAP5 analyses was to help understand the phenomena observed in the experiment. The main phenomena of interest were the natural circulation flow of water through the passive safety injection system lines and the condensation phenomena in the CMT.

Figure 1 presents the comparison CMT tank pressure from the GDE-05 experiment and from CATHARE2, RELAP-5 calculations. The pressure in the CMT oscillates slightly at about 2000 seconds of the transient The reason for oscillation is condensation in the CMT, which occurs when steam begins to flow to the CMT; Figure 2 presents the injection mass flow rate from the CMT. During the first 1000 seconds after the break opening flow through the CMT is single phase liquid flow, and the injection line flow rate in low. At about 2000 seconds of experiment steam and water mixture begins to flow to the CMT, and the injection line mass flow rate begins to oscillate. After about 500 seconds of oscillating flow steam begins to flow to the CMT and the injection flow rate stabilises to a higher level.

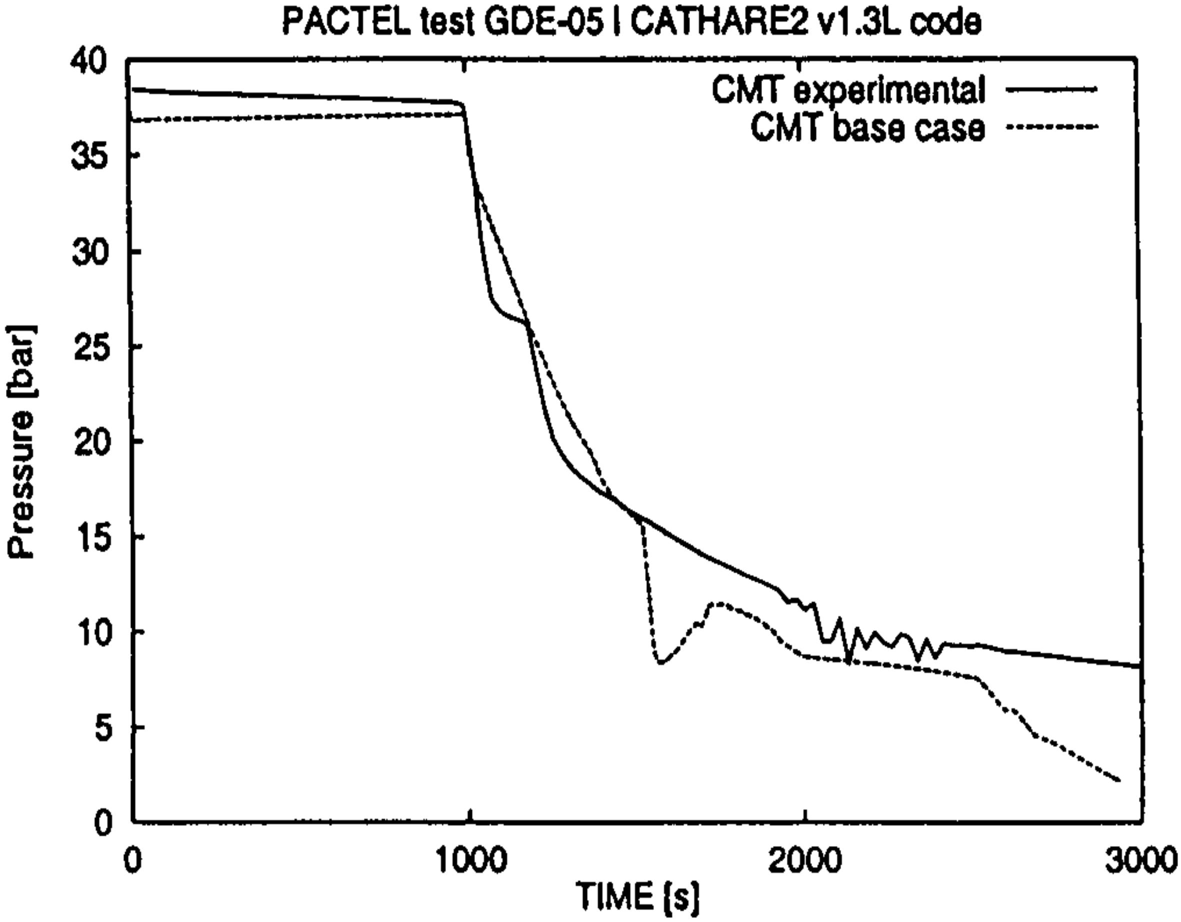

Figure 1: CMT pressure.

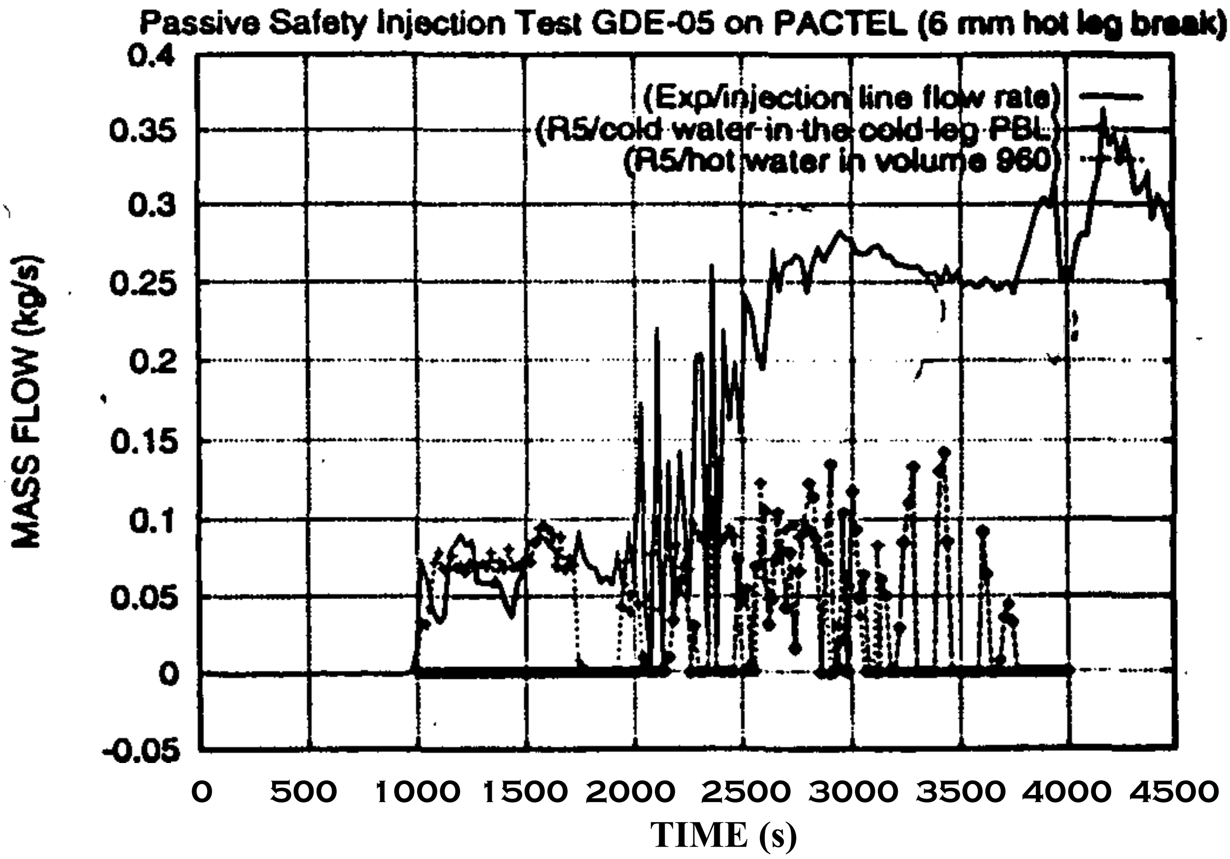

Figure 2: Calculated flow rate in the cold leg PBL and measured flow rate in the injection line. GDE-05 experiment.

Comparison of calculated and measured results show that the biggest deviation between results occurs when steam appears.
2.2 The SPES-2 tests were performed as part of the ALWR program sponsored by the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI). Westinghouse, in cooperation with SIET (Societa' Informazioni Espcrienze Termoidrauliche), ENEL (Ente Nazionale Energia Elettrica), ENEA (Ente per le Nuove Tecnologie, 1'Energia e 1'Ambiente), and Ansaldo, performed the SPES-2 tests to obtain data on the integrated behavior and performance of the AP600 passive systems to support validation of the computer codes to perform the licensing safety analyses for the AP600. The SPES-2 test matrix includes eight different LOCA simulations with a wide selection of sizes and location in order to observe the integrated operation of the passive system over a wide range of conditions. Moreover three Steam Generator Tube Ruptures (SGTR) and one Main Steam Line Break (MSLB) have been performed.
The results of WCOBRA/TRAC simulation had been compared with the test results [2]. Due to the rapid loss of pressure down to saturation pressure for the core and upper plenum, core boiling initiates and upper plenum flashes while the fluid level decreases down to the hot leg elevation. Comparison between prediction and data is presented. Comparison show that, in the period from 300 to 2500 s after the start of emergency cooling, the amplitude of oscillations of the mass flow rate of the coolant can become very large. The results of calculations using

the WCOBRA/TRAC code do not give a detailed description of the dynamics of the mass flow rate in this time interval.
2.3 The mathematical model worked out in [5] for parametrical oscillations of the coolant due to a periodic change in the elasticity of the latter enables us to determine the boundary (critical) value of the modulation of this parameter. This model for revealing in more detail the dynamic processes in the coolant of the passive protection systems for the core was proved to be applicable.

3 Investigation

It is shown that in two-phase media, the pressure increment Δp is directly proportional to the increase in the acoustic compliance ΔC.
Assuming that the pressure p in the reactor varies in time t with a frequency of Ω and an amplitude of p_a

(1) $$p = p_0 + p_a \cdot \sin(\Omega t)$$

and introducing the notation

(2) $$p_a / p_0 = \chi \text{ and } const / p_0 = C_0$$

(where the subscript "0" indicates that the value of the parameter at time t=0 should be taken, and χ is the modulation index), we obtain the following expression:

(3) $$C(t) = C_0 \frac{1}{1+\chi \cdot \sin(\Omega t)}$$

With small oscillations of the pressure, the velocity, or the temperature of the two-phase coolant, the acoustic compliance of the two-phase medium changes the most. In view of this, a linear differential equation with periodic coefficients for the circulation circuit of the reactor under consideration should be analysed to obtain trustworthy results:

(4) $$\frac{d^2V}{dt^2} + 2\lambda \frac{dV}{dt} + \omega_0^2 (1 + \chi \cos \Omega t) V = \theta$$

here $$\omega_0^2 = \frac{1}{MC}$$

$$\lambda = \frac{r}{2M}$$

where V is volume of two-phase mixture; ω_0 is eigen frequency of the coolant in the reactor circuit; r is the acoustic resistance; C is the acoustic capacitance and M is acoustic mass of media.
The method of r, M, C, calculation was worked out.
The equation (4) gives possibility establish boundary conditions of self-excitation PO.
In case $\Omega = 2\omega_0$ and assuming that λ is small value these boundary conditions are determined by χ_{cr} as:

(5) $$\chi_{cr} = 2r\sqrt{\frac{C}{M}} = \frac{2}{Q} = 2\delta ,$$

where Q is Q factor of the circulation circuit, and δ is damping factor for the oscillations in the circuit. The critical value of the modulation index χ_{cr} corresponds to the boundary conditions under which PO arise. Omitting the intermediate steps of the transformation we obtain

(6) $$\chi_{cr} = \frac{v_m}{\alpha_m}\left(\frac{\rho_m}{\rho_w}\right)^{1/2}\left(\frac{\Delta h_{out}}{\Delta h_{inl}}\right)^{1/2}\left(\xi_{fr}\frac{l}{d} + \sum \xi_{loc}\right)$$

here $\Delta h_{out} = h_{out} - h_s$ and $\Delta h_{inl} = h_s - h_{inl}$

here V is flow velocity, α is propagations velocity of small pressure disturbances, ξ_{fr} is resistance factor of friction, ξ_{loc} is local resistance factor, h is coolant enthalpy, l is steam generating channel (SGC) length, d is SGC diameter. Index: m is mixture, w is water, s is saturation, inl is inlet, out is outlet. Using (2) and (6) we obtain

(7) $$P_a^{cr} = P\frac{v_m}{\alpha_m}\left(\frac{\rho_m}{\rho_w}\right)^{1/2}\left(\frac{\Delta h_{out}}{\Delta h_{inl}}\right)^{1/2}\left(\xi_{fr}\frac{l}{d} + \sum \xi_{loc}\right)$$

And for SGC without local resistances as follows:

(8) $$P_a^{cr} = \xi_{fr} P \frac{l}{d}\frac{v_m}{\alpha_m}\left(\frac{\rho_m}{\rho_w}\right)^{1/2}\left(\frac{\Delta h_{out}}{\Delta h_{inl}}\right)^{1/2}$$

At $P_a < P_a^{cr}$ the thermal-hydraulic disturbance (pressure, flow rate) amplification can be occurred only in resonant case.

Eigen frequencies of coolant oscillations may coincide with the eigen frequencies of oscillations of the equipment or of its individual items (it amounts to resonant interaction between the equipment id the coolant). In these cases, the amplitude of oscillations of the coolant, as well as of the equipment itself, increases. The probability that such conditions will arise becomes greater for changes in the way the items are mounted for normal operation, and also during transients.

Even short-term resonant interaction between the coolant and the equipment (during transients, for example) can greatly reduce the service life of the equipment and/or the parts of the constructions; in certain cases, it may be the cause of an accident.

4 Summary

The worked out model describes mathematically the mechanism for exciting parametrical oscillations when the compressibility of the steam-water mixture varies periodically. The frequency of these oscillations depends not only on the parameters of the thermal-hydraulic processes, but also on the geometrical dimensions of the heat-removal system and the stage of the process of cooling down the core. An analysis of the model indicates that the phenomenon of parametrical oscillations appears under certain combinations of the above-mentioned factors. A detailed list of these factors includes the intensity of steam formation, the structure of the two-phase flow, the configuration and dimensions of the elements that form the PSIS [6]. The new dimensionless product – c**riterion of steam generating ducts parametrical similarity (CSPS)**. The main goal of CSPS utilisation in PSIS area is optimisation of reactor core protection and operation control.

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Footnotes

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